U-Pb zircon geochronology and Sm-Nd-Pb isotopic constraint for Precambrian plutonic rocks in the northeastern part of Ryeongnam massif, Korea

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The Ryeongnam massif is composed of Precambrian gneisses, Paleozoic and Mesozoic sedimentary rocks and extensive Triassic-Jurassic plutonic rocks of felsic to mafic composition. In the northeast Ryeongnam massif, the oldest rocks belong to the Sobaegsan gneiss complex, which is composed of orthogneisses, paragneisses and mafic plutonic rocks. U-Pb zircon ages for the felsic and mafic intrusive bodies within the Sobaegsan gneiss complex are: the Icheon granite gneiss, 2357 ± 43 and 2342 ± 47 Ma; the Buncheon granite gneiss, 1963 ± 5 Ma; the Pyeonghae granite gneiss, 1936 ± 21 Ma; the Ogbang amphibolite, 1918 ± 10 Ma; the Imwon leucogranite gneiss, 1826 ± 20 Ma. The Hyeondong biotite schist, which is intruded by the Buncheon granite gneiss and the Ogbang amphibolite, yielded an age of 2271 ± 44 Ma. The Nd-Sm-Pb isotopic data indicate that the felsic plutonic rocks are derived from an older Archean crust. The Nd TDM ages are Archean, and the εNd values are negative for the felsic rocks and positive for the amphibolite. Common Pb isotope compositions also indicate a crustal source for the felsic intrusives. The U-Pb ages of Precambrian rocks of the Ryeongnam massifs are similar to those in the Gyeonggi massif, and may have a similar crustal evolutionary history. The Precambrian rocks of South Korea could be related either to the North China block or to the South China block, as the isotope ages and patterns are not unique to either block. Similarly, a geologic correlation with Japan, although possible, is tenuous at present.

INTRODUCTION

The Korean peninsula, like much of East Asia, is a mosaic of micro continental blocks that was formed by the accretion and collision of several continental blocks (Hsu et al., 1990; Kim and Turek, 1996; Kim et al., 1999; Klimetz, 1983; Li et al., 1993; Sengor, 1985; Turek and Kim, 1995). In the simplest subdivision, the Korean peninsula is made up of three massifs, two mobile belts and one volcanogenic basin (Fig. 1). The Nangrim massif is a high grade Precambrian terrain with outliers of Phanerozoic (Cambrian to Holocene) rocks. The Cambrian-Ordovician rocks here are an extension of the North China platform sedimentation. The Imjingang fold belt is made up of late Permian to Early Triassic rocks (Cho et al., 1995; Ree et al., 1996); it separates the Nangrim and Gyeonggi massifs. The Gyeonggi massif is dominated by Mesozoic felsic plutons that intrude the Precambrian gneisses and the Paleozoic sedimentary rocks and in turn are overlain by Cretaceous rocks. The Gyeonggi and the Ryeongnam massifs are separated by the Ogcheon belt, which is a fold and thrust belt involving Precambrian to Jurassic rocks. The Ogcheon basin was initiated in an in-
tra plate setting (Kwon and Lan, 1991) in the late Proterozoic and underwent a series of compressional deformations in the Mesozoic (Koh and Kim, 1995). Contact between the Ogcheon belt and the Ryeongnam massif is the Honam shear zone, a dextral strike slip fault (Cluzel et al., 1991; Kwon and Ree, 1997; Yanai et al., 1985). The bedrock of the Ryeongnam massif is predominantly a Precambrian and a Mesozoic igneous rock terrain. The Precambrian igneous rocks of the Ryeongnam massif are divisible into: felsic plutonic rocks having a 2100–1700 Ma age, and basic gabbroic to anorthositic plutonic complexes having a 1700 Ma age (Kwon and Jeong, 1990; Turek and Kim, 1996). In the south, the Ryeongnam massif borders with the volcanoclastic Gyeongsang basin. Both the Imjingang and the Ogcheon belts are major tectonic zones and represent continental collision zones (Yin and Nie, 1993). There is, however, considerable uncertainty as to which of these two belts is a possible continuation of the Qinling-Dabie-Sulu belt of China, which is regarded as the collision zone of the North China block (NCB) and the South China block (SCB) (Fig. 1).

Orogenic events in the Korean Peninsula are attributed to block movements associated with the
collision of the North and the South China blocks and the subduction of the paleo-Pacific plate during Early Mesozoic. Overall, the Triassic growth of the east Eurasian landmass is primarily due to the continental collision of the NCB and SCB (Chough et al., 2000; Hacker et al., 1998; Li, 1999; Yin and Nie, 1993). The effects of these collisions in China and Korea may also be extended to Japan. The Precambrian orthogneiss clasts in the Kamiaso conglomerate of the Mino terrain in central Japan could be derived from the northeastern part of the Ryeongnam massif (Suzuki and Adachi, 1994), and more specifically from the Ryeongnam Samcheok gneiss (Adachi and Suzuki, 1995).

In general the existing non U-Pb isotope ages are not primary and do not date time of emplacement, as they tend to reflect younger events. Moreover, they lack the precision that zircon ages can provide. The source of the plutonic material, either primary or recycled crust, is not known. In this study, we provide 7 U-Pb zircon ages. This is an extension of ages measured by us in the Jirisan segment of the Ryeongnam massif (Kim et al., 1999; Turek and Kim, 1995, 1996). To elucidate the origin of the plutonic material we have measured Nd-Sm-Pb isotopic compositions.

**GENERAL GEOLOGY**

Precambrian rocks of the Ryeongnam massif are ortho- and para-gneisses, with the former being more abundant. The Ryeongnam massif is divided into two terrains the Sobaegsan gneiss complex in the northeast, and the Jirisan gneiss complex in the southwest (Lee, 1973). Both terrains have been affected by three metamorphisms, though the low-grade schists of the Sobaegsan complex apparently experienced only one metamorphic event (Chough et al., 2000; Lee and Kim, 1984). Lithologically the two terrains are similar. Metasedimentary rocks, in particular quartzite and calc-silicate rocks, are somewhat more abundant in the Sobaegsan complex than in the Jirisan complex. Attempts at classifying the metasedimentary rocks stratigraphically (Kim et al., 1963) have not been successful due to structural complexities. The Jirisan complex contains anorthosite, which is absent in the Sobaegsan complex. In the Sobaegsan gneiss complex, the paragneisses are migmatitic gneiss, banded gneiss, granitic gneiss, metapelite, quartzite, schist, phyllite and calc-silicate rock, while the orthogneisses are granite gneiss, leucogranite and amphibolite. In the Jirisan gneiss complex, the paragneisses are migmatitic gneiss, granitic gneiss, banded gneiss, augen gneiss, amphibolite and schist while the orthogneisses are granite gneiss, porphyroblastic gneiss, leucogranite gneiss and anorthosite. Mutually gradational contacts between the various gneisses are common.

Phanerozoic sedimentary rocks cover the Precambrian basement in the northwest part of the Ryeongnam massif (Fig. 1). The Cambrian-Ordovician Chosun Supergroup is essentially a carbonate succession with minor sandstone and shale. The overlaying Carboniferous-Triassic Pyeongan Supergroup is marginal-marine and non-marine clastic succession with economically significant coal measures.

Important and critical to the designation of the Ryeongnam terrain as a massif are syn-tectonic and post-tectonic plutonic rocks that were emplaced during the Triassic-Jurassic (Songrim-Daebo) orogenies. Compositionally these plutons are calc-alkali series granite, granodiorite, syenite, diorite and gabbro (Kim, 1990). The age of the Daebo granites suggests that the Daebo orogeny is equivalent to the Nevadan orogeny in North America, an early phase of the Yenshan orogeny of China, and a mid phase of the Sakawa orogeny in Japan (Chough et al., 2000). Mesozoic granites of the northeast Ryeongnam massif are various phases of a batholith, ca. 20–40 ×10–20 km that is elongate in a NE-SW direction. This batholith, along its northern margin, is intrusive into the Precambrian gneisses; Cretaceous volcanic rocks cover its southern margin and this places a minimum age on this body. Near the Yecheon shear zone, the granitic rocks are foliated. This foliation is the result of ductile deformation at depth related to dextral strike slip movement along the Yecheon shear zone, which it is a
branch of the Honam shear zone (Chang, 1991; Hong and Lee, 1989).

**Petrology and geologic setting of plutonic rocks**

**Icheon granite gneiss (KJ-98A, KJ-98B)** is a ca. 120 km² batholith composed of massive, pale gray to dark gray, medium- to coarse-grained granite gneiss that displays a strong gneissosose structure produced by recrystallized bands of quartz and biotite having a strike of N30–50°E. The major minerals are quartz, plagioclase, K-feldspar, biotite, garnet and chlorite. Abundant xenoliths of pelitic, psammitic and basaltic compositions are derived from the gneiss complex. Most xenoliths are rounded or ellipsoidal in shape, and range from a few cm to 3–5 m. The Icheon granite gneiss intrudes the Sobaegsan gneiss complex; and in turn is intruded by Precambrian leucogranite gneiss and by Jurassic plutons. The sample collected for age determination, KJ-98A, is a coarse-grained, massive granodiorite from the margin of the body near the town of Imwon. Another sample collected from the central part of the body, KJ-98B, is also a granodiorite.

**Granitic gneiss (KJ-72A, KJ-72B)** is a typical paragneiss of the Sobaegsan gneiss complex and is extensively distributed. It is light gray to gray in color, medium- to coarse-grained with an N30–50°E gneissosity produced by recrystallized quartz and biotite. It grades into schist, banded gneiss and migmatitic gneiss. It is intruded by Precambrian Buncheon, Pyeonghae and Imwon plutons and by Mesozoic plutons. The samples collected, between the towns of Hyeondong and Pyeonghae, are coarse-grained biotite gneisses.

**Buncheon granite gneiss (KJ-69A, KJ-69B)** forms a large batholith (ca. 300 km²) and several stocks around the town of Uljin. The rock is a light pink, medium to coarse-grained granite gneiss with an N35–60°E gneissosity produced by recrystallized quartz and biotite. Small-scale augen structures, 2–2.5 cm in diameter, are mostly perthite, less frequently, microcline with blebs of quartz, plagioclase and biotite. Major, trace and rare element study by Hong (1992) identifies this batholith as a syn-collisional granite. It is intrusive into the Sobaegsan gneiss complex and is intruded by Precambrian Ogbang amphibolite and Imwon leucogranite gneiss, and by Mesozoic plutons. The samples collected, near the town of Imwon, are coarse-grained granite.

**Pyeonghae granite gneiss (KJ-81, KJ-67A)** occurs as a large batholith (ca. 250 km²) and several stocks along the East Sea coastline in the Pyeonghae and Uljin regions. The dominant rock types are augen and porphyroblastic gneisses. The augen and porphyroblast blebs are 3–8 cm in diameter and are mostly microcline and quartz, with minor biotite, garnet and plagioclase. The mineral composition and texture of the Pyeonghae granite gneiss is similar to the porphyroblastic gneiss of the Kurye-Hadong region of southwestern part of the Ryeongnam massif (Turek and Kim, 1996). It is intrusive into metavolcanics, biotite schist, crystalline limestone, and amphibolite of the Sobaegsan gneiss complex. In turn, it is intruded by Precambrian leucogranite gneiss and by Mesozoic plutons. A Pb-Pb isochron age of 2093 ± 86 Ma has been reported by Cheong et al.
(2000) for this pluton. The samples collected, near the town of Pyeonghae, are coarse-grained augen granite gneisses.

**Ogbang amphibolite (KJ-80, KJ-80A)** is a dark gray, fine- to coarse-grained member of an intermediated to mafic intrusive. Field evidence indicates that in the crystallization sequence of this pluton the coarse pegmatitic gabbro phase is older, than the amphibolite, while the fine- to medium-grained hornblende diorite is younger. Geochemical studies, major, trace and rare earth elements indicate that this pluton formed in a continental back arc basin from tholeiitic upper mantle basalt (Chang et al., 1993). It intrudes the Hyeondong granitic gneiss of the Sobaegsan gneiss complex and the Buncheon granite gneiss. Samples collected, near the Ogbang tungsten ore deposits, are a coarse-grained amphibolite with euhedral to subhedral hornblende phenocrysts.

**Imwon leucogranite gneiss (KJ-87A) batholith** (ca. 180 km²) is a medium- to coarse-grained leucocratic granite gneiss that locally grades into a pegmatite. Garnet porphyroblasts, occasionally replaced by yellowish biotite and chlorite, are commonly observed close to the contacts with metasedimentary rocks. This rock intrudes the Buncheon, Pyeonghae and Hongjesa granite gneisses as well as phyllite, biotite schist and calcic silicate rocks of the Sobaegsan gneiss complex. In turn, it is intruded by Jurassic plutons. Choo and Kim (1986) report a Rb-Sr whole rock age of 2089 Ma and an initial 87Sr/86Sr of 0.7108. The sample collected, near the town of Imwon, is coarse-grained granite.

**Previous age determinations**

Isotopic ages for Precambrian rocks of the Ryeongnam massif are sparse, particularly in the northeast. There are Rb-Sr and Pb-Pb whole rock ages for felsic orthogneisses that range from 2.2 to 1.6 Ga, though most are between 2.1 and 1.8 Ga (Choo and Kim, 1986; Choo, 1987; Cheong et al., 2000; Kim et al., 1978; Kim and Lee, 1983; Kwon et al., 1995; Park et al., 1993). A Sm-Nd whole rock age of 1047 ± 69 Ma has been obtained for a biotite gneiss in the northern part of the Jirisan complex (Lee et al., 1992), while an older age of 2250 ± 4 Ma on garnet has been reported for the leucogneiss in the eastern part of the Sobaegsan complex (Lee et al., 1994). An anorthosite body near the southeastern margin of the Jirisan gneiss complex has a Sm-Nd age of 1678 ± 90 Ma (Kwon and Jeong, 1990) and is similar to the age of the Damiao anorthosite in North China. Kim (1986) reports Ar-Ar ages of 1318 to 1998 Ma for granitic and porphyroblastic gneisses in the southwestern part of Ryeongnam massif. A charnockite from the Jirisan complex has a Sm-Nd garnet age of 1820 ± 11 Ma (Kim et al., 1998). Also, in the southwestern part of the Ryeongnam massif Turek and Kim (1995, 1996) report 9 U-Pb zircon ages of 2120–1766 Ma for Proterozoic plutons. Cheong et al. (2000) reported a garnet Pb-Pb age of 1840 ± 26 Ma for a garnet-biotite schist from the northeast Ryeongnam massif. The ages reported here for the Sobaegsan gneiss complex corroborate the 2.1 to 1.9 Ga for the granite gneisses of the Jirisan gneiss complex and indicate that there was significant felsic igneous activity during the late Paleoproterozoic to early Mesoproterozoic in the Sobaegsan and the Jirisan terrains. Lan et al. (1995) determined crustal residences ages (TDM) for 8 samples and report ages of 1.65 to 3.18 Ga, and more than half of ages are older than 2.19 Ga. It is clear from above that the Ryeongnam massif has a long history of crustal evolution. Ages determined by Rb-Sr, Sm-Nd, Ar-Ar, Pb-Pb have many limitations and frequently relate to prior or subsequent geologic events other than age of emplacement. The many K-Ar ages determined for Precambrian rocks in the Ryeongnam massif are generally not primary ages having been affected by numerous younger thermo/tectonic events, or they may contain inherited Ar, hence are not cited here.

**Analytical Procedures**

**U-Pb geochronology**

Zircons were separated from 30 kg samples by standard procedures using a Wilfley table, heavy liquids and Carpco and Frantz magnetic separa-
tors. Fractions selected for analyses were upgraded by abrasion and hand picking, and were cleaned thoroughly by ultrasonic vibration in 50% nitric acid and ultra pure water. Sample dissolution was done in Teflon pressure vessels using HF and HNO₃ acids (Krogh, 1973; Parrish, 1987); they were spiked with a mixed ²⁰⁸Pb and ²³⁵U tracer for the concentration measurements.

The Pb and U isotopic ratios were measured either on an NBS design mass spectrometer at University of Windsor or on an extended geometry VG sector mass spectrometer at the University of Kansas. The Pb composition was measured on unspiked aliquots. The U and Pb concentrations and the U/Pb isotopic ratios were calculated from spiked aliquot runs. Uncertainties in the U/Pb ratios are ±0.5%, precision of the ²⁰⁷Pb/²⁰⁶Pb and ²⁰⁸Pb/²⁰⁶Pb is ±0.1% at the 95% confidence limit (CL). The absolute error in the ²⁰⁴Pb/²⁰⁶Pb is a function of the magnitude of the ratio but is less than 0.000010. Isotopic ratios were corrected for mass fractionation (0.10% per amu), blank (Pb 25 pg), and initial common Pb (Stacey and Kramers, 1975).

Data reduction, plotting and regression analysis (Ludwig, 2001) produced concordia diagrams with lower and upper intercept ages. The mean square of weighted deviates (MSWD), which is a residual variance, is a measure of the goodness of fit of the data points. Data is collinear within experimental error if the MSWD <1. The age uncertainties reported here are 95% CL.

Sm-Nd-Pb isotopic analysis

For the Sm-Nd-Pb isotope ratios, approximately 100 mg of rock powder was dissolved with a mixed acid (HF : HClO₄ : HNO₃ = 4:1:1) in a Teflon vessel. Sm and Nd were separated by a two-step cation/anion exchange technique (Makishima et al., 1993). Pb was extracted by anion exchange technique using an HBr medium. Isotope ratios were measured using a VG 54-30 thermal ionization mass spectrometer at the Korea Basic Science Institute (KBSI). ¹⁴³Nd/¹⁴⁴Nd ratios were normalized to ¹⁴⁶Nd/¹⁴⁴Nd = 0.7219. Replicate analyses of La Jolla Nd standard were ¹⁴³Nd/¹⁴⁴Nd = 0.511842 ± 0.000005 (N = 13, 2σ SE). Sm and Nd concentrations were determined by isotope dilution using a ¹⁴⁸Sm,¹⁵⁰Nd spike. Pb isotope data were corrected based on replicate analyses of NBS 981 Pb standard. Procedural blanks were: <0.4 ng for Sm and Nd, <0.1 ng for Pb.

RESULTS

The analytical results are in Tables 1 and 2, and Figs. 2–10. Sample descriptions and locations are in Appendix A.

U-Pb ages

Icheon granite gneiss (KJ-98A) This rock contains zircons that are euhedral to subhedral. They are pink to brown in color, translucent to transparent, stubby to elongate, and strongly fractured. Three fractions define line that intercepts the concordia curve at 2357 ± 43 and 910 ± 150 Ma (Fig. 2). Fraction C registers an older age. All 4 fractions are strongly, 26–37%, discordant.

Icheon granite gneiss (KJ-98B) Another sample collected from the central portion of the Icheon granite gneiss has zircons that are similar as those found in sample KJ-98A, which came from the margin of this body. In this sample the zircons are darker brown and somewhat longer, but they are also strongly fractured. Five zircon fractions separated from this rock are collinear and produce concordia intercepts of 2342 ± 47 and 1464 ± 61 Ma (Fig. 3). The fit of the points is very good and as evident from the MSWD of 0.53, but the 5 points are extremely, 39–63%, discordant.

Icheon granite gneiss (KJ-98B) Another sample collected from the central portion of the Icheon granite gneiss has zircons that are similar as those found in sample KJ-98A, which came from the margin of this body. In this sample the zircons are darker brown and somewhat longer, but they are also strongly fractured. Five zircon fractions separated from this rock are collinear and produce concordia intercepts of 2342 ± 47 and 1464 ± 61 Ma (Fig. 3). The fit of the points is very good and as evident from the MSWD of 0.53, but the 5 points are extremely, 39–63%, discordant.

Hyeondong biotite schist (KJ-95) The zircons isolated from this rock are euhedral, pink, transparent, multifaceted and stubby, free of fractures, inclusions and alteration. Three of the 4 fractions analyzed are collinear and produce concordia intercepts of 2271 ± 44 and 772 ± 347 Ma MSWD 1.03 (Fig. 4). The 4 fractions are strongly discordant, 14–20%, which results a large error in the age. Fraction A, however, plots to the right of the discordia and indicates the presence of an older component.
**Buncheon granite gneiss (KJ-69A)** This rock contains zircons that are euhedral, yellow to honey brown in color, with a vitreous luster. Two of the 4 fractions measured are concordant; the 4 points define a discordia well within experimental error (MSWD = 0.19). The concordia intercept ages are $1963 \pm 5$ and $440 \pm 160$ Ma (Fig. 5).

**Pyeonghae granite gneiss (KJ-81)** Zircons in this rock are euhedral, light brown and transparent. The larger grains are fractured. Six fractions were analyzed and on the concordia diagram they plot close together being 19–27% discordant. The fit of the points is within experimental error and concordia intercept ages are $1936 \pm 21$ and $31 \pm 130$ Ma (Fig. 6).

![Concordia plot for Icheon granite gneiss (KJ-98A).](image)

![Concordia plot for Icheon granite gneiss (KJ-98B).](image)
Table 1. Analytical data for zircons from northeastern Ryeongnam massif, Korea

<table>
<thead>
<tr>
<th>Sample detail</th>
<th>Sample No.</th>
<th>Magnetism</th>
<th>Grain size (µm)</th>
<th>Weight (mg)</th>
<th>Concentration (ppm)</th>
<th>U</th>
<th>Pb</th>
<th>Pb$<em>{206}$/Pb$</em>{207}$</th>
<th>Pb$<em>{207}$/Pb$</em>{206}$</th>
<th>Pb$<em>{208}$/Pb$</em>{206}$</th>
<th>Pb$_{206}$/U</th>
<th>Atomic ratios</th>
<th>Apparent ages (Ma)$^{(a)}$</th>
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<td>2223</td>
</tr>
<tr>
<td>Buncheon granite gneiss (KJ-69A)</td>
<td>A</td>
<td>m0 Hp</td>
<td>114</td>
<td>0.7</td>
<td>974</td>
<td>360</td>
<td>0.00066</td>
<td>0.07823</td>
<td>0.12839</td>
<td>5.855</td>
<td>0.3527</td>
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<td>1955</td>
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<tr>
<td>B</td>
<td>m1 Ab</td>
<td>114</td>
<td>0.7</td>
<td>1159</td>
<td>408</td>
<td>0.00015</td>
<td>0.05678</td>
<td>0.12134</td>
<td>5.738</td>
<td>0.3467</td>
<td>1919</td>
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<td>1957</td>
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<tr>
<td>C</td>
<td>m0 Ab,Hp</td>
<td>62</td>
<td>0.5</td>
<td>297</td>
<td>110</td>
<td>0.00069</td>
<td>0.07477</td>
<td>0.12564</td>
<td>5.891</td>
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<tr>
<td>D</td>
<td>m1 Ab,Hp</td>
<td>62</td>
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<td>1126</td>
<td>373</td>
<td>0.00012</td>
<td>0.05184</td>
<td>0.12005</td>
<td>5.389</td>
<td>0.3282</td>
<td>1830</td>
<td>1883</td>
<td>1943</td>
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<tr>
<td>Pyeonghae granite gneiss (KJ-81)</td>
<td>A</td>
<td>m1 Ab</td>
<td>62</td>
<td>4.2</td>
<td>1663</td>
<td>463</td>
<td>0.00014</td>
<td>0.02733</td>
<td>0.12022</td>
<td>4.597</td>
<td>0.2815</td>
<td>1599</td>
<td>1749</td>
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<tr>
<td>B</td>
<td>m0</td>
<td>62</td>
<td>4.2</td>
<td>2031</td>
<td>518</td>
<td>0.00004</td>
<td>0.02459</td>
<td>0.11847</td>
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<td>0.2596</td>
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<td>m1-5 Ab</td>
<td>114</td>
<td>3.3</td>
<td>1123</td>
<td>280</td>
<td>0.00008</td>
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<td>0.11917</td>
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<td>0.11881</td>
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<tr>
<td>E</td>
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<td>4.3</td>
<td>1965</td>
<td>531</td>
<td>0.00001</td>
<td>0.02384</td>
<td>0.11821</td>
<td>4.486</td>
<td>0.2754</td>
<td>1568</td>
<td>1729</td>
<td>1929</td>
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<tr>
<td>F</td>
<td>m1-2 Ab</td>
<td>62</td>
<td>4.2</td>
<td>5421</td>
<td>1377</td>
<td>0.00010</td>
<td>0.01957</td>
<td>0.11980</td>
<td>4.230</td>
<td>0.2590</td>
<td>1485</td>
<td>1680</td>
<td>1933</td>
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</table>
Relative magnetic susceptibility of zircons is reported as m0 (nonmagnetic) to m5 (paramagnetic) and is related to the inclination of the Frantz isodynamic separator using maximum current of 2 A. Grain size is an average; sieves used were 85, 150, 75, 38 µm. Ab is abraded. Hp is totally handpicked.

Measured ratio.
Blank corrected.
Blank and nonradiogenic Pb corrected.
Decay constants used: $\lambda_{238} = 1.55125 \times 10^{-10}$ year$^{-1}$; $\lambda_{235} = 9.8485 \times 10^{-10}$ year$^{-1}$ (Steiger and Jäger, 1977).

Table 2. Sm-Nd-Pb isotopic composition of Precambrian rocks from northeastern Ryeongnam massif, Korea

<table>
<thead>
<tr>
<th>Sample</th>
<th>GC-Sobaegsan gneiss complex</th>
<th>BG-Buncheon granite gneiss</th>
<th>PG-Pyeonghae granite gneiss</th>
<th>OA-Ogbang amphibolite</th>
</tr>
</thead>
<tbody>
<tr>
<td>KJ-72A</td>
<td>GC</td>
<td>0.511342</td>
<td>5.62</td>
<td>3.55</td>
</tr>
<tr>
<td>KJ-72B</td>
<td>GC</td>
<td>0.511700</td>
<td>3.93</td>
<td>17.78</td>
</tr>
<tr>
<td>YH-03</td>
<td>GC</td>
<td>0.511349</td>
<td>5.11</td>
<td>28.33</td>
</tr>
<tr>
<td>PH-26</td>
<td>GC</td>
<td>0.511375</td>
<td>11.88</td>
<td>61.05</td>
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<tr>
<td>KJ-69A</td>
<td>BG</td>
<td>0.512121</td>
<td>1.58</td>
<td>5.50</td>
</tr>
<tr>
<td>KJ-69B</td>
<td>BG</td>
<td>0.511302</td>
<td>4.98</td>
<td>26.85</td>
</tr>
<tr>
<td>KJ-81</td>
<td>PG</td>
<td>0.511717</td>
<td>6.22</td>
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<td>FG</td>
<td>0.511290</td>
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</tr>
<tr>
<td>PH-17</td>
<td>FG</td>
<td>0.511251</td>
<td>6.78</td>
<td>38.20</td>
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<tr>
<td>KJ-80</td>
<td>OA</td>
<td>0.512746</td>
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<td>7.53</td>
</tr>
<tr>
<td>KJ-80A</td>
<td>OA</td>
<td>0.512814</td>
<td>2.78</td>
<td>8.40</td>
</tr>
</tbody>
</table>

GC- Sobaegsan gneiss complex, BG- Buncheon granite gneiss, PG- Pyeonghae granite gneiss, OA- Ogbang amphibolite.
Calculated for $t = 2$ Ga.
Ogbang amphibolite (KJ-80) The abundance of zircons in this rock is low. They are euhedral to subhedral, light yellow in color, they have a dull luster, a shuttered appearance, and contain magnetite inclusions. The Th content of the zircons is high as evident from the high Pb\(^{208}/\text{Pb}^{206}\) ratios (Table 1). Three fractions measured are 3–8% discordant and yield concordia intercept ages of 1918 ± 10 and 18 ± 270 Ma (Fig. 7). A regression forced through zero lower intercept gives an age of 1917 ± 7.5 Ma.

Imwon leucogranite gneiss (KJ-87A) This rock contains subhedral elongate zircons, dark brown in color. The 4 fractions analyzed are very discordant, 40–52%. The concordia intercept ages are 1826 ± 20 and 167 ± 40 Ma (Fig. 8).
**Sm-Nd-Pb isotopic data** The Sm-Nd-Pb data is in Table 2 and shown diagrammatically, Figs. 9 and 10. The $\varepsilon$Nd and depleted mantle ages, $T_{DM}$, for the 8 samples analyzed here range between $-4.97$ and $+3.4$ and $2.56$ to $3.37$ Ga, respectively. The common Pb isotope compositions define a secondary isochron having an age of $2074 \pm 100$ Ma.

**DISCUSSION**

**U-Pb Geochronology**

The Icheon granite gneiss (KJ-98A and B) dated here has an age of $2357 \pm 43$ and $2342 \pm 47$ Ma. This pluton cuts metasedimentary rocks, such as mica schist, quartzite and fine-grained...
amphibolite. It also contains xenoliths of metasedimentary rocks. The Hyeondong biotite schist (KJ-95), which is paragneiss, is younger at 2271 ± 44 Ma. Both the gneiss and the schist contain an older component as evident from the isotope data (Figs. 2 and 4). It is unfortunate that the zircons separated from these rocks are highly discordant, as this results in large errors in the ages.

Such high discordance has not been found in other Precambrian rocks that we have dated in Korea (e.g., Kim et al., 1999). The Icheon granite gneiss is now the oldest plutonic rock discovered in Korea. In the Gyeonggi massif still older rocks, the Inje crystalline schist 2413 ± 21 Ma and the Gongju migmatitic gneiss 2417 ± 39 Ma (Turek and Kim, 1996), have been dated, however, these are paragneisses.

It is noteworthy that the Icheon granite gneiss and the Hyeondong biotite schist have high, Middle/Late Proterozoic, lower intercept ages (1464, 910, 772 Ma). Generally, in the Ryeongnam and the Gyeonggi massifs lower intercepts tend to be Mesozoic. There is, however, evidence of Middle/Late Proterozoic igneous activity in Korea. Zircon ages for the Seosan and the Hongseong granite gneisses are 1766 ± 26 and 687 ± 5 Ma, respectively (Turek and Kim, 1996). Lee et al. (1998) reports a zircon age of 755.8 ± 1.3 Ma for a metarhyolite. Cho (2001) sees an 822–812 Ma SHRIMP age preserved in zircons from an orthogneiss. There are also several metamorphic ages by other schemes, e.g., 794 ± 162 Ma by common Pb method for a marble (Park et al., 1993). All of which lends support to the existence of igneous/metamorphic activity in Middle/Late
Proterozoic that can explain the observed high lower intercept ages.

It appears that widespread plutonism in both the Ryeongnam and the Gyeonggi massifs took place at 1918–1963 Ma. The Buncheon granite gneiss, (KJ-69A) has an age of 1963 ± 5 Ma. Previous, less precise, ages for this body are 1930 ± 19 Ma (Kim et al., 1989). The Pyeonghae granite gneiss (KJ-81) is 1936 ± 21 Ma, and the Ogbang amphibolite (KJ-80) is 1918 ± 10 Ma old. A Pb-Pb age for the Pyeonghae granite gneiss is 2093 ± 86 Ma (Cheong et al., 2000). In the southwestern Ryeongnam massif various granite and porphyroblastic gneisses have ages of 1923, 1928, 1934, 1935, 1945 Ma while in the Gyeonggi massif the Hongcheon porphyroblastic gneiss has an age of 1952 ± 13 Ma (Kim et al., 1999).

The Imwon leucogranite gneiss (KJ-87A) dated here at 1826 ± 20 Ma is the youngest granite gneiss in the Ryeongnam massif. However, in the Gyeonggi massif comparable and even younger ages have been reported. There is the Seongnam migmatite 1868 ± 9 Ma and the Seosan granite gneiss 1766 ± 26 Ma and even still younger plutons such as the Kanghwa granite gneiss 1673 ± 10 Ma, and the Hongseong granite gneiss at 687 ± 5 Ma (Kim et al., 1999; Turek and Kim, 1996).

The existing U-Pb age database is small; but it does not appear that the Ryeongnam and the Gyeonggi massif plutonic activity was markedly different in terms of emplacement ages. In fact, it seems that 1918–1963 Ma was a widespread plutonic event in Korea. There have been numerous K-Ar, Rb-Sr, Sm-Nd, Pb-Pb and Ar-Ar ages reported for rocks in the Ryeongnam and the Gyeonggi massifs. While some of them agree with U-Pb ages, many tend to be younger. However, there is a tendency for these ages to cluster at 1900–2000 Ma. It therefore appears that the Ryeongnam massif and the Gyeonggi massif are not distinct terrains, or at least were physically very close together, and have experienced coeval plutonic events that need not be cogenetic. This is in keeping with Cheong et al. (2000) who contend that the Ryeongnam and the Gyeonggi massifs are the same crustal block.

**Sm-Nd and Pb constraints**

Nd model ages, T\(_{DM}\), give an indication of possible ages of the source materials, while \(\varepsilon_{Nd}(0)\), and \(\varepsilon_{Nd}(t)\) parameters indicate presence of assimi-
lated material. $T_{DM}$ ages reported here (Table 2) are $2.48-3.37 \text{ Ga}$, and 10 of the 11 ages are Archean. The $\varepsilon_{\text{Nd}}(0)$ and $\varepsilon_{\text{Nd}}(t)$ values are negative for 9 of the 11 samples, which indicate that these rocks have been assimilated or are derived from older crustal material. Cheong et al. (2000) reports similar results; 11 out of 13 samples, also from the northeastern Ryeongnam massif, have Archean $T_{DM}$ ages and negative $\varepsilon_{\text{Nd}}$ values. Lan et al. (1995) determined Sm-Nd model ages for basement rocks from South Korea and found that 15 out of 34 samples gave Archean model ages, with a few older than 3.0, up to 3.8 Ga. Two Ogbang amphibolite samples measured here (KJ-80 and KJ-80A, Table 2) have positive $\varepsilon_{\text{Nd}}$ values, as this is a mafic pluton we believe that this material is derived from a less contaminated, more primitive, mantle source. Chang et al. (1993) proposed an upper mantle origin for this amphibolite on the bases of its trace and rare earth element composition. It is also apparent from the Sm-Nd diagram, Fig. 9, that these two amphibolite samples are distinct.

The inheritance of Archean crustal materials is also evident from U-Pb zircon upper concordia intercept ages; e.g., $3294 \pm 196 \text{ Ma}$ for a Proterozoic (683 Ma) gneiss in the Gyeonggi massif (Turek and Kim, 1996). There are 22 Permian to Jurassic U-Pb zircon ages in South Korea (Gyeonggi and Ryeongnam massifs) reported by Kim and Turek (1996), Kim et al. (1999), and Turek and Kim (1995). These are concordia lower intercept ages; the upper intercept ages are all Precambrian (5 are Archean, rest Proterozoic).

The isotopic composition of Pb measured on whole rocks (Table 2) plot on a Pb-Pb diagram (Fig. 10) above the Stacey and Kramers (1975) Pb evolution curve and therefore indicates a crustal signature, typical of recycled material. The data form a linear array yielding an isochron age is $2074 \pm 100 \text{ Ma}$ which is a hybrid age as the samples represent different plutons.

**Correlations with China and Japan**

Existing U-Pb zircon ages for Precambrian rocks in China and Japan have been compiled and

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**Fig. 11.** Single frequency age plot of U-Pb zircon ages in S. Korea (Gyeonggi and Ryeongnam massifs), Hida belt, North China block and South China block. The dotted and filled symbols are Ryeongnam massif and Hida belt ages, respectively. In this plot each age has a frequency of one. Identical ages will plot vertically above each other. Data sources: Gyeonggi massif (Turek and Kim, 1996; Kim et al., 1999); Ryeongnam massif (Turek and Kim, 1995, 1996); Hida belt (Sano et al., 2000; Hidaka et al., 2002); North China block (Pidgeon, 1980; Sun, 1984; Liu et al., 1985, 1992; Pecut and Jahn, 1986; Li et al., 1987; Qiao et al., 1987; Shen et al., 1987; Dai et al., 1990; Sun et al., 1991; Wu et al., 1991, 1998; Bai et al., 1992; Wang, 1993; Hu, 1994; Wang et al., 1995; Guo and Shi, 1996; Song et al., 1996; Kröner et al., 1998; Wilde et al., 1998; Mao et al., 1999; Su et al., 1999; Guan et al., 2002); South China block (Lianzhao, 1989; Zhang et al., 1989; Kröner et al., 1993; Ames et al., 1993, 1996; Wang et al., 1995, 2000; Rowley et al., 1997; Hacker et al., 1998; Xie et al., 1998; Zhao, 2000; Li et al., 2002).
plotted on a single frequency diagram, Fig. 11. From this it is apparent that overall the North China block is older than the South China block, which is generally the accepted view (e.g., Chen and Jahn, 1998; Jahn et al., 1999). It can also be seen that ca. 2500 Ma extensive igneous activity occurred in the North China block. Both the North China block and Korea experienced major plutonic activity at 1900–2000 Ma, which is practically absent in the South China block. In Japan there are no Precambrian rocks, however, a Precambrian provenance for some of the clastic material in the Hida and the Mino terrains has been established by Nd-Sr isotopes and by U-Pb zircon dating (Arakawa et al., 2000; Sano et al., 2000; Hidaka et al., 2002). U-Pb zircon SHRIMP ages for clasts from the Kamiaso conglomerate in the Mino terrain date the source region at 1850 to 1950 Ma though some zircon domains are older, highest age being 3254 Ma. These clast ages are shown on Fig. 11 and they appear to blend into the Korean population of ages. It has been proposed that the Kamiaso conglomerate clasts may have been derived from rocks of the Ryeongnam massif (Adachi and Suzuki, 1995; Sano et al., 2000).

In China available Sm-Nd isotope data (Chen and Jahn, 1998; Guan et al., 2002; Huang et al., 1986; Jahn et al., 1999; Sun et al., 1992;) confirm that the North China block is older than the South China block (Fig. 9). Archean terrains are wide spread in the North China block (Jahn and Zhang, 1984; Jahn et al., 1988; Liu et al., 1985, 1990, 1992; Song et al., 1996), but are limited in the Yangtse and the Cathaysian terrains of the South China block (Chen and Jahn, 1998). Lan et al. (1995) showed that the North and the South China blocks have some overlapping Nd model ages and that South Korea (Gyeonggi, Ogcheon and Ryeongnam) is better related to the South China block than the North China block. On the other hand, also based on Nd isotope data, Chen and Jahn (1998) interpretation is that the Gyeonggi massif is related to the North China block, the Ryeongnam massif to the South China block, and the Ogcheon fold belt is the equivalent of the Qinling-Dabie-Sulu belt. The Sm-Nd plot, Fig. 9, shows that 9 of the 11 samples analyzed plot on the boundary between the North China block and the South China block domains. This fails to resolve the problem of affiliation of the Korean rocks in the Ryeongnam and Gyeonggi massifs to either the North China block or the South China block.

The Hida belt of Japan has occupied a part of the eastern margin of the Asian continent. However, there is still no consensus on its position relative to Korea and China before the Triassic. The correlation of the Hida belt with the Korean Peninsula and China remains in dispute. To constrain the location and provenance of rocks of the Hida belt, Arakawa et al. (2000) correlates the belt with the Korean Peninsula and eastern China. Shoma et al. (1990) proposed that the Hida belt might tectonically correspond to an eastern extension of Qinling-Dabie-Sulu belt (suture) in eastern China. The Hida gneisses have Nd model ages of 0.5–2.2 Ga (Arakawa et al., 2000). By contrast, the metamorphic rocks of the Gyeonggi massif, the Ogcheon fold belt and the Ryeongnam massif in South Korea have more variable and lower 143Nd/144Nd ratios and higher, 1.5–3.8 Ga, model ages (Lan et al., 1995) than in the Hida belt. According to Arakawa et al. (2000), some of the Gyeonggi massif, the Ryeongnam massif and the Ogcheon belt data coincide with the Hida belt data having middle Proterozoic model ages.

CONCLUSIONS

U-Pb zircon ages for 6 plutons and one paragneiss in the northeastern Ryeongnam massif are: 2357, 2342, 2272, 1963, 1936, 1918, and 1826 Ma. The age of the Ichon granite gneiss, based on two samples, is 2357 and 2342 Ma. This is now the oldest igneous plutonic rock in Korea, and it places a minimum age on some of the ortho- and para-gneisses of the Sobaegsan gneiss complex. The above ages are comparable to published U-Pb zircon ages for rocks in the southwestern part of the Ryeongnam massif. Igneous activity in the Ryeongnam massif was probably continuous from 2357 to 1826 Ma; however, the peak period of
plutonic activity appears to be 1963 to 1918 Ma. Plutonism in the Ryeongnam massif is essentially coeval with that in the Gyeonggi massif and thus it appears that these two massifs may be parts of the same tectonic block. If this is so then the Imjingang fold belt, rather than the Ogcheon belt, is likely to be the extension of the Qinling-Dabie-Sulu belt of China.

Sm-Nd-Pb isotope data indicates that many of the Precambrian plutons were derived from older Archean materials. The Nd T_{DM} ages determined here range from 2.48 to 3.37 Ga, and together with existing published data, indicate derivation from an Archean protolith. The εNd(t) values for the felsic rocks are negative (−3.13 to −4.93), and positive (2.1 and 2.57) for the amphibolite sample. This shows that the felsic rocks are derived from recycled crustal material while the amphibolite is largely of mantle origin. An older crustal component is also apparent from the common Pb isotopic composition measured on whole rocks. These Pb isotopic compositions are radiogenic isotope enriched and plot above the normal Pb growth curve.

Evaluation of available U-Pb ages and Sm-Nd isotope data for China confirms the established and accepted notion of the distinctiveness of the North and South China blocks. The Korean Ryeongnam and Gyeonggi massifs can belong to the North or the South China blocks, as the U-Pb ages and Nd-Sm data fall into an area of overlap between the two China blocks. Geologic connections to Japan are more tenuous. Sm-Nd data for the Hida belt indicates presence of a Proterozoic component. Clasts in the Kamiaso conglomerate have dominantly Proterozoic ages. Thus, a Korean provenance for these rocks is a possibility.

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REFERENCES


Liu, D. Y., Shen, Q. H., Zhang, Z. Q., Jahn, B. M. and


APPENDIX A:

PETROGRAPHY AND SAMPLE LOCATION

Icheon granite gneiss (KJ-98A)

This is strongly foliated, a medium- to coarse-grained, massive granodiorite. It consists of plagioclase, microcline, biotite, quartz, sphene, apatite, zircon, allanite and opaque minerals. Secondary minerals are garnet, epidote, chlorite, sericite and calcite. This sample comes from the margin of the pluton near the town of Imwon. Latitude 37°11′36″ N, longitude 129°17′48″ E.

Icheon granite gneiss (KJ-98B)

This is strongly foliated, a dark gray, a medium- to coarse-grained granodiorite having gray quartz and gray feldspar. It consists of plagioclase, microcline, biotite, quartz, sphene, apatite, zircon, allanite and opaque minerals. Secondary minerals are garnet, epidote, chlorite, sericite and calcite. This sample is from the central part of the pluton. Latitude 37°12′58″ N, longitude 129°16′31″ E.

Gneiss complex (KJ-72A)

Strongly deformed coarse-grained quartzofeldspathic gneiss blends gradually into migmatic gneiss and banded gneiss. The rock consists of: quartz, plagioclase, microcline, biotite, garnet, chlorite. Accessories are: titanite, apatite, and zircon. Secondary minerals are sillimanite, cordiariite, sericite, calcite, and epidote. Latitude 36°54′25″ N, longitude 129°14′01″ E.

Gneiss complex (KJ-72B)

Medium- to coarse-grained granitic gneiss with metasedimentary relics of quartzite, calc schist, and a chlorite aggregate. It consists of quartz, plagioclase, biotite, garnet, and chlorite. Accessory minerals are magnetite, apatite, and zircon. Secondary minerals are epidote, sillimanite, cordiariite, sericite, and calcite. Latitude 36°55′03″ N, longitude 129°20′09″ E.

Hyeondong biotite schist (KJ-95)

Strongly deformed fine- to medium-grained rock derived from metasedimentary rocks. It con-
sists of biotite, quartz, garnet, and plagioclase. The quartz and biotite, is recrystallized and deformed by dynamic metamorphism. Accessory minerals are magnetite, apatite, zircon, and epidote. Secondary minerals are epidote, garnet, chlorite, sericite, and calcite. Latitude 36°50′25″ N, longitude 129°07′02″ E.

Buncheon granite gneiss (KJ-69A, 69B)
This rock is a strongly foliated, massive, coarse-grained, light pink, granite. It consists of plagioclase, microcline, hornblende, recrystallized quartz and biotite. Mineral presents are: quartz, plagioclase, K-feldspar, biotite, opaques, titanite, zircon, apatite, and secondary sericite, chlorite and epidote. Latitude 36°57′05″ N, longitude 129°17′42″ E.

Pyeonghae granite gneiss (KJ-67A)
This sample is a mylonitized granite having a porphyroblastic texture. It is a coarse-granied deformed rock with 4–12 cm subrounded to subangular felsic porphyroblasts, quartz is reoriented and recrystallized, biotite has kink cleavage, plagioclase has deformed albite twins. The rock consists of: quartz, plagioclase, microcline, biotite, hornblende, and garnet. Accessory minerals are: magnetite, apatite, titanite, and zircon. Secondary minerals are chlorite, sericite, and epidote. Latitude 36°47′10″ N, longitude 129°27′40″ E.

Pyeonghae granite gneiss (KJ-81)
This rock is a coarse-grained deformed rock with porphyroblastic to augen texture. It consists of plagioclase, microcline, hornblende, recrystallized quartz and biotite, opaques, apatite, titanite, zircon, and secondary chlorite, sericite, and epidote. Latitude 36°45′01″ N, longitude 129°28′50″ E.

Ogbang amphibolite (KJ-80, 80A)
This rock is hypidiomorphic, medium to coarsed grain gabbro with euhedral to subhedral 10–20 mm hornblende phenocrysts. It is composed of hornblende, plagioclase, biotite, augite, titanite, opaques, zircon, and apatite and small amount of secondary chlorite and sericite. Latitude 36°54′57″ N, longitude 129°09′48″ E.

Imwon leucogranite gneiss (KJ-87)
Major minerals of this rock consist of quartz, microcline, plagioclase (An 6–10 ) which makes this a leucocratic rock. Muscovite, garnet, zircon, chlorite and epidote occur as minor constituents. Quartz and feldspar show mortar texture and fractured plagioclase twin. Myrmekitic texture of plagioclase as the result of symplectic intergrowth of vermicular quartz on host plagioclase, indicates its association with alkali metasomatism. Latitude 37°13′26″ N, longitude 129°20′26″ E.